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SUMMARY

An ultrasonic system was developed and used to observe the formation of fatigue cracks in center-notched sheet specimens of unalloyed aluminum, two aluminum alloys, a mild steel (approx 0.035 percent carbon), and a nickel-base alloy. The reflection technique was used to detect minute fatigue cracks. The through-transmission technique was used to a limited extent to measure relatively long cracks. Actual lengths of detected cracks were determined by microscopic examination. Stress-life (S-N) curves of life to initial detectable cracks as well as S-N curves of life to fracture were obtained.

The reflection technique was used while the test was in progress to detect fatigue cracks that ranged in length approximately from 0.0005 to 0.005 inch for unalloyed aluminum, mild steel, and Inconel and from 0.0005 to 0.0025 inch for 6061-T6 and 2014-T6 aluminum alloys. In the sharply notched specimens utilized in this investigation, cracks were detected within approximately 1 to 3 percent of total specimen life for all the materials over the range of stresses considered.

It was possible to detect smaller cracks with the reflection technique than with the through-transmission technique. The instrument output from cracks longer than approximately 0.010 inch, however, was more reproducible when the through-transmission technique was used.

The effects of crack orientation on instrument output with the reflection technique was studied by means of slots machined into flat plates. Slot surfaces normal to the direction of the ultrasonic waves produced the greatest voltage output. The farther the slot deviated from a position normal to the wave direction, the smaller the output became, even though the slot surface area when projected on a plane normal to the wave direction was constant.

INTRODUCTION

Fatigue involves the processes of crack initiation and crack propagation prior to fracture. Any method that can be used to detect small fatigue cracks nondestructively during the course of a fatigue test would be extremely useful as a research tool. If the method could also be successfully applied in the field, its usefulness would be even greater.

Methods are presently available that can be used to detect fatigue cracks, but generally speaking, each has associated difficulties, more or less severe, depending on the intended application. For example, commonly used inspection methods such as penetrating-liquid, magnetic-particle, and radiographic techniques, when applied to fatigue specimens, all require interruption of the fatigue test. Additional limitations exist because the penetrating-liquid and magnetic-particle techniques can only be used to detect cracks at or near the surface, and the use of X-ray techniques poses problems of safety and interpretation.

Optical microscopy, another obvious technique, requires highly polished surfaces and generally involves the termination of the test and the sectioning of the specimens prior to microscopic examination. Testing many specimens for different time intervals makes it possible to determine when extremely small cracks have formed. Such a procedure is both expensive and very time consuming. A recent refinement of this procedure (ref. 1) involves the production of replicas of the specimen surface suitable for use in either the electron or the light microscope. Plastic replicas were obtained while the specimens remained in the fatigue machine by simply stopping the test periodically. From these replicas, cracks less than 0.0001 inch deep were detected in flexure specimens after relatively few load applications; however, detection of cracks by this method requires highly polished specimens and still involves lengthy procedures.

In an attempt to detect fatigue cracks more simply and without interruption of the test, electrical and ultrasonic methods have recently been introduced. These techniques are not as sensitive for detecting extremely small cracks as the microscope but they have practical advantages because they generally can be more easily applied. An electric potential technique has been used to determine slow crack growth in tensile tests (refs. 2 and 3). The feasibility of crack detection by electrical impedance measurements has also been demonstrated (refs. 4 and 5). Changes in the electrical resistance of notched rotating-beam-type specimens (ref. 4) were correlated with depth of fatigue cracks. The smallest cracks that could be detected with certainty were on the order of 0.005 inch in depth.

Ultrasonic methods, which have been widely used for nondestructive inspection purposes, have recently been used to observe damage in fatigue specimens. Ultrasonic surface waves have been used (ref. 6) to detect surface flaws in bending fatigue specimens, but crack sizes were not determined in this study. Very recently, ultrasonic inspection techniques were used (ref. 7) to detect cracks in thin (0.039 in.) center-notched steel sheet specimens that were tested in axial fatigue. Cracks ranging from 0.003 to 0.004 inch in length were detected.

Of the methods described, the ultrasonic method was selected for further study in the present investigation. This method afforded certain advantages because it was not limited to the detection of surface cracks, did not require the interruption of the fatigue test, and could be used with many materials regardless of their electrical or magnetic properties. Also, this method does not require that specimens be insulated from the test apparatus as is necessary for the electrical methods. A program was therefore initiated at the NASA Lewis Research Center to further develop the ultrasonic method and to apply it to fatigue testing of various materials. Axial tensile fatigue tests were run with center-notched sheet specimens of unalloyed aluminum, two aluminum alloys, a mild steel, and a nickel-base alloy. Stress-life (S-N) curves based on life to initial detectable cracks as well as S-N curves of life to fracture were obtained. Metallographic studies were made to measure actual lengths of the detected cracks.

DEVELOPMENT OF ULTRASONIC FATIGUE-CRACK-DETECTION SYSTEM

Principles of Ultrasonic Crack Detection

The principles of ultrasonic wave propagation can be found in references 8 to 10. A brief review of the theory involved, a description of the crack-detection system, and the manner of its application are presented in the following sections.

Fatigue-crack detection by reflection technique. - Detection of fatigue cracks by the reflection of ultrasonic energy is similar to the use of radar in the detection of distant objects. Acoustic energy, in the form of pulsed envelopes of high-frequency waves, is transmitted from a transducer into the test specimen. After the pulse is transmitted, the transducer acts as a receiver for energy reflected from any discontinuity in the specimen. The metal-air interface of a fatigue crack constitutes such a discontinuity. The low density of air and the relatively low velocity of ultrasonic waves in air result in an acoustic mismatch that causes the reflection of incident ultrasonic waves. The amount of energy reflected from a crack is directly related to the crack area, the intensity of the incident ultrasonic wave, and the orientation of the crack.

Fatigue-crack detection by through-transmission technique. - A second technique for the detection of discontinuities by means of ultrasonic energy does not depend on the measurement of reflected energy. It employs two transducers: one acts as a transmitter, the other as a receiver. The principle of operation is based on the fact that a crack in the region of the specimen between the transducers will decrease the energy transmitted to the receiver. The amount of energy received is inversely related to the crack area.

A limit on the size of the smallest crack that can be detected with this technique is imposed by the requirement that a very small change in an initially large signal must be measured. Under these conditions, small changes can be difficult to resolve.

System Design

A block diagram of the ultrasonic crack-detection system is shown in figure 1. A commercial ultrasonic flaw detector was used in this investigation. The commercial unit contained a pulse generator to drive the piezoelectric

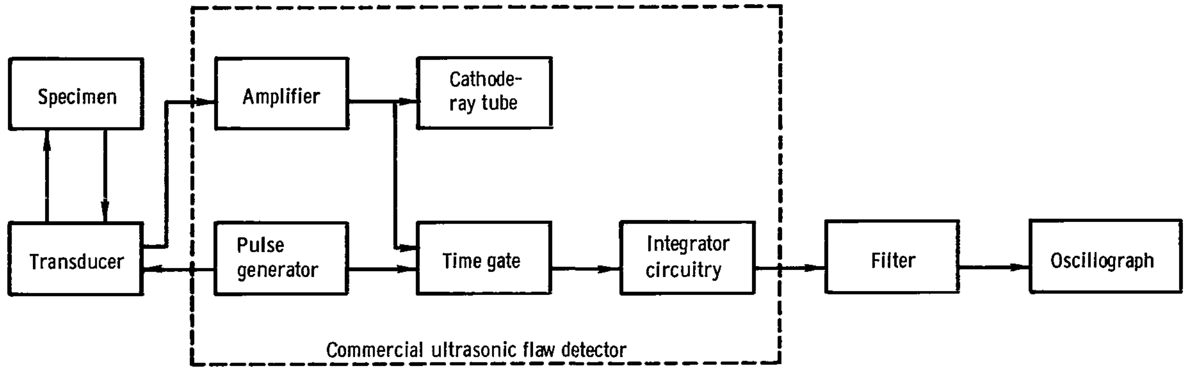


Figure 1. - Crack-detection system.

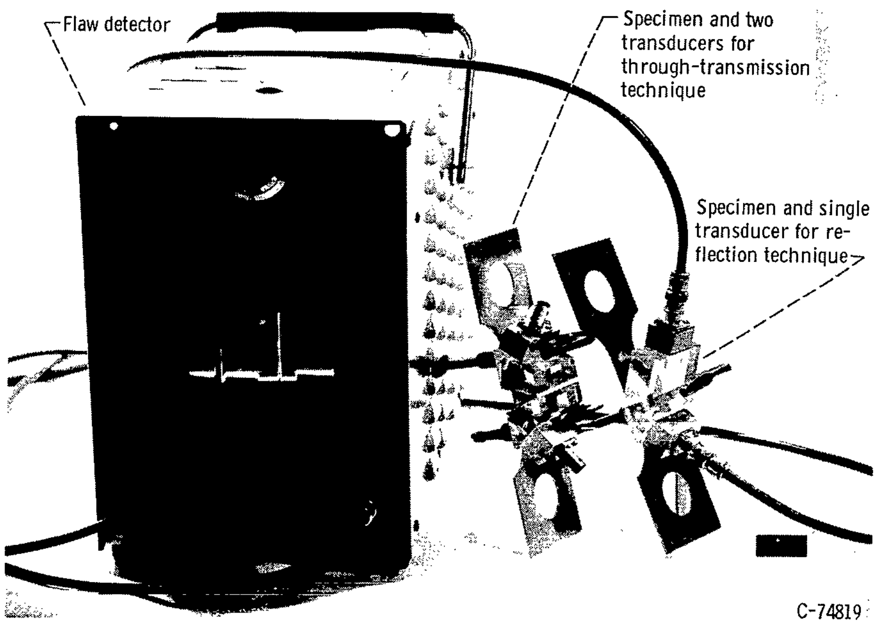
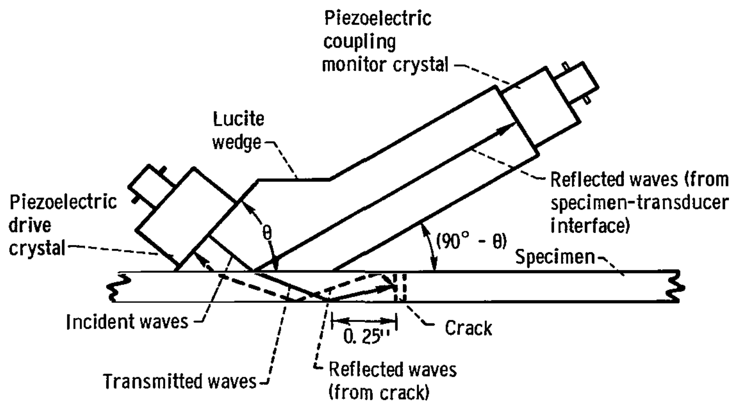


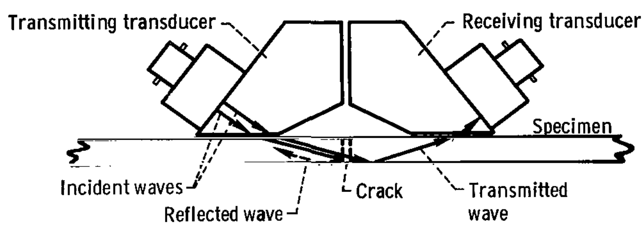
Figure 2. - Commercial flaw detector and test specimens with attached transducers.

crystal. It also contained the necessary amplifiers and a cathode-ray tube that amplified and displayed the reflected energy pattern, and time gating and integrator circuitry. A filter and an oscillograph were added. The oscillograph was used to obtain a permanent record of the signal reflected from the notch or crack in the specimen. The commercial transducer was modified to permit its application to the detection of fatigue cracks in notched-sheet specimens. A photograph of the commercial flaw detector and specimens with attached transducers for use with the reflection and through-transmission techniques is shown in figure 2.

Ultrasonic transducer design. - Figure 3 shows a sketch of the transducer designs used with the crack-detection device. The transducer used with the



(a) Transducer used with reflection technique.



(b) Transducers used with through-transmission technique.

Figure 3. - Schematic diagram of ultrasonic transducers used with crack-detection device.

reflection technique consisted of a lucite wedge on which were mounted two piezoelectric crystals (fig. 3(a)). A rectangular (1.0 by 0.5 in.) piezoelectric crystal was used to generate ultrasonic waves of fixed frequency and to receive the reflected signals. Utilization of this transducer design with sheet fatigue specimens permitted the test section to be flooded with shear (transverse) waves. The direction of vibration in shear waves is transverse to the direction of wave propagation.

The shear-wave mode was used because it permitted ultrasonic energy to be transmitted through the specimen surface and subsequently to be propagated along the length of the specimen. Also, the velocity of shear waves is one-half that of the longitudinal waves. This permitted detection of smaller flaws because of the decreased wavelength associated with the shear wave.

The wave mode and the angle of entry of the ultrasonic waves into the test specimen were controlled by the wedge angle θ and the refraction of the incident waves at the wedge-specimen interface. It was necessary that the wedge material have an acoustical propagation velocity less than the shear wave velocity in the specimen materials. Lucite plastic possessed the required velocity characteristic. The optimum wedge angle θ was experimentally determined for each fatigue specimen material by the method of reference 11. These data are summarized in table I.

It was also necessary to provide a coupling medium between the wedge and the fatigue specimen to eliminate air from the interface and to allow the trans-

TABLE I. - WEDGE ANGLE FOR MAXIMUM ULTRASONIC SHEAR WAVE AMPLITUDE IN SPECIMEN MATERIALS

Material	Specimen thickness, in.	Wedge angle, deg
2014-T6 Aluminum	0.060	53.5
6061-T6 Aluminum	.064	53.5
1100 Aluminum	.064	53.5
Mild steel	.053	46.0
Inconel	.046	46.0

mission of the ultrasonic waves into the specimen. The coupling medium must have an acoustical impedance similar to that of the wedge and the specimen and be sufficiently fluid to fill all air pockets. Because changes in thickness of the coupling layer would affect the amount of energy transmitted to the specimen, a fluid that would tend to retain its consistency during the test was required. The coupling material used in this investigation was a molybdenum disulphide lubricant normally used to prevent seizure of mating parts at high temperature. Other coupling materials, an epoxy type bonding agent for example, provided good transmission prior to testing, but the bond quickly failed in fatigue because the transducer was positioned on a stressed area of the specimen.

Although a rather high degree of coupling efficiency was attained with the molybdenum disulphide lubricant, not all of the ultrasonic energy generated in the wedge by the drive crystal was transmitted to the specimen because of the discontinuity at the wedge-specimen interface. The energy that did not enter the specimen was reflected back into the wedge as shown in figure 3(a). Changes in the intensity of these reflected waves during the course of a test were indicative of changes in coupling efficiency. An additional crystal (coupling monitor crystal) was mounted on the other end of the wedge to monitor these changes. This crystal was used only as a receiver and was manually switched to the amplifier input at intervals. In general, the changes in the intensity of the reflected waves detected by this crystal were small. The distance from the wedge-specimen interface to the coupling monitor crystal was such that energy reflected from the wedge-monitor crystal interface reached the drive crystal well after any reflections from the cracks within the specimen were received. This insured that intrawedge reflections would not be interpreted as specimen cracking.

When the through-transmission technique was used, two transducers were needed: one to transmit ultrasonic waves, the other to receive them (fig. 3(b)). As may be seen from the figure, some of the ultrasonic waves introduced to the specimen pass through it and are detected by the receiving transducer. Some of the waves are reflected from the crack (dotted arrow) and are therefore not detected by the receiving transducer. Space limitations precluded the use of coupling monitor crystals when this technique was utilized. The coupling efficiency was assumed to remain essentially constant.

<u>Special transducer characteristics and their relation to transducer design</u>. - Although lucite has acoustical properties suitable for providing wave refraction and is readily machinable, it has a limitation in that attenuation of ultrasonic waves in this medium is much greater than it is in metals. Thus a limitation was imposed on the maximum frequency that could be used because attenuation of ultrasonic energy at higher frequencies is much greater than it is at low frequencies. The higher the wave frequency (shorter wavelength),

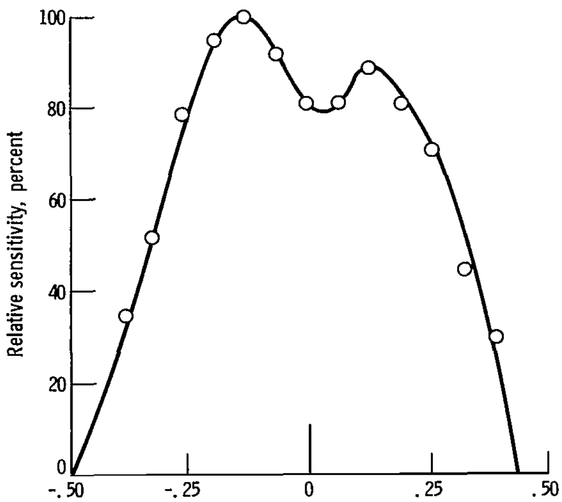


Figure 4. - Variations in sensitivity across typical 1-inch transducer. Distance from flaw, 0.25 inch.

however, the smaller the flaw that can be detected. Consequently, a crystal was chosen that had as high a frequency as possible without encountering excessive ultrasonic wave attenuation in the wedge. It was experimentally determined that a frequency of 5 megacycles was the practical maximum with the available equipment.

Comparisons made of several 5-megacycle, 1.0- by 0.5-inch crystals disclosed variations in their response to the presence of flaws. In order to obtain repeatability in the experiments, the crystals were not interchanged.

Plots were also made of the variations in relative sensitivity to flaws across the long dimension of each crystal. Variations were determined by measuring the reflected energy from a 0.050-inch-long slot in an aluminum alloy sheet as the transducer was moved laterally past the slot. Measurements were taken at intervals of approximately 0.06 inch. A plot showing the variation in sensitivity for the 1.0-inch crystal used in this investigation is shown in figure 4. The crystal was mounted on a 53.5° wedge, and measurements were made at a distance of 0.25 inch from the flaw. The general shape of the curve is typical of all the crystals checked. The central variations can be attributed to "near zone" effects. When the reflecting surface lies within an area very near the transducer (near-zone), interference patterns can cause maximums and minimums in the energy received at the crystal as a function of flaw location. When the distance from crystal to flaw was relatively large (approx 3 in.), only a single sensitivity peak was observed.

After the region of maximum sensitivity of the transducer was determined, the transducer was subsequently mounted on fatigue specimens to utilize this region to advantage. Despite the near-zone sensitivity patterns, the positioning of the transducer approximately 1/4 inch from the test section of the specimen provided optimum crack measurement sensitivity because wave attenuation and dispersion were minimized.

Operation of system electronics. - Ultrasonic pulses were transmitted at the rate of 500 per second with a pulse time of about 1 microsecond. Since a typical velocity for ultrasonic shear waves in the specimens used in this investigation was about 0.1 inch per microsecond, sufficient time was provided between pulses for all reflected signals to return to the drive crystal when the reflection technique was employed. A reflection signal from the end of the specimen would return to the drive crystal after reflections from flaws in the test section had been received. These reflected pulses were reconverted to electrical signals by the drive crystal, amplified, and displayed on the cathode-ray tube.

When the through-transmission technique was employed, only that portion of the ultrasonic pulse which was not reflected by specimen discontinuities was received by the receiving transducer. It was not necessary to allow time between pulses for the reflected signals to return to the crystal.

The commercial ultrasonic equipment included a time gate and integrator circuitry (fig. 1, p. 4). The gate allowed only the reflected (or transmitted) signals occurring within a preselected time interval after each transmitted pulse to pass through to the integrator circuitry. Since the distance traveled by an ultrasonic pulse is proportional to time, the time gate may be interpreted as a "propagation-distance" gate. The output of the amplifier was therefore gated for the specimen position at which fatigue cracking was expected to occur when the reflection-technique was used. Extraneous reflections from the transducer-specimen interface and reflections from the end of the specimen were blocked by this gate. With the through-transmission technique the amplifier was gated for the time at which the transmitted pulse reached the receiver.

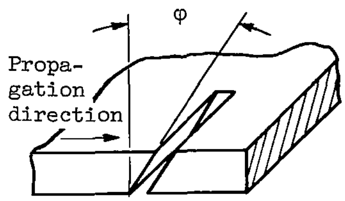
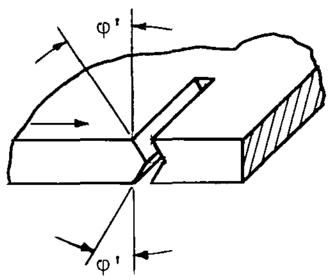
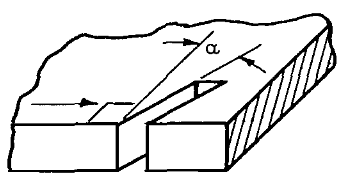
The integrator circuitry provided a dc (direct current) voltage level proportional to the signal that passed through the time gate. After the signal was filtered to remove minor fluctuations in the integrator output, the resulting dc voltage was recorded on an oscillograph. Changes in the recorded dc voltages were proportional to changes in the amount of ultrasonic energy received. Sensitivity could be increased by proper adjustments of the amplifier and the integrator circuitry.

Output voltage as a function of flaw orientation. - Fatigue cracks may be either in a position normal to the direction of propagation of the ultrasonic waves or at some angle to them. An attempt was made to determine the effect of macroscopic crack orientation on the amplitude of ultrasonic waves received by the transducer when the reflection technique was employed.

Slots 0.05 inch in length were machined through a 0.060-inch-thick aluminum alloy plate to simulate crack surfaces at various angles to the ultrasonic waves. These slot configurations and the corresponding normalized output voltages are shown in table II. The projected area of each configuration was maintained equal with respect to the direction of wave propagation. The angle between the slot and a plane normal to the plate is designated as φ for uniplanar slots and as φ' for biplanar slots. The angle between the slot and a plane normal to the edge of the plate is designated as α.

The output from each slot shown in the table is relative to the output from a slot lying normal to the direction of the ultrasonic waves. The transducer-to-slot distance was set at 0.25 inch for all tests (see fig. 3(a)). The arrows in the flaw orientation sketches indicate the propagation direction of the ultrasonic pulses. The amplitude of the reflected wave decreased as the orientation of the slot varied from a position normal to the ultrasonic wave (table II). The output for variations in φ and φ' can be approximated by the cosine function for the given angle. The decrease in output with an increase in α is much more pronounced than the decrease that occurs with an increase in φ. This pronounced decrease might be expected because a value of α of 45° would reflect ultrasonic energy in a direction parallel to the

TABLE II. - OUTPUT VOLTAGE AS FUNCTION OF FLAW ORIENTATION

Flaw	Orientation angle, deg	Normalized output voltage
$\alpha = 0^{\circ}$	φ	
	0	1.00
	10	.96
	30	.96
	45	.74
$\alpha = 0^{\circ}$	φ'	
	0	1.00
	30	.81
	45	.75
$\varphi = 0^{\circ}$	α	
	0	1.00
	10	.92
	30	.30
	45	.00

transducer face and would theoretically result in zero output.

The results obtained with slots of predetermined orientation can be applied to explain differences in ultrasonic reflection from fatigue cracks whose surfaces lie at different angles with respect to the direction of ultrasonic waves. Thus, a crack that lies on the macroscopic shear plane of a specimen would not appear as large as one lying normal to the specimen surface when the direction of the ultrasonic waves is parallel to the specimen axis.

Because the use of the through-transmission technique depends primarily on a blocking of the transmitted waves by the projected area of a crack, the technique is relatively independent of crack orientation. Consequently, the effect of crack orientation on output voltage was not investigated for this technique.

MATERIALS AND FATIGUE TEST PROCEDURE

Specimen Materials

Five materials were tested in axial tensile fatigue: unalloyed aluminum, two aluminum alloys (6061-T6 and 2014-T6), mild steel (approx 0.035 percent carbon), and Inconel. These materials represent three classes of widely used metals of different densities and attenuation characteristics. The tensile strengths of notched specimens are listed in table III. Sheet specimens were employed, with thicknesses ranging from 0.046 inch for Inconel to 0.064 inch for unalloyed aluminum. A sketch of the test specimens is shown in figure 5. Center-notched specimens were used so that eccentric loading would be reduced after cracks were formed and, also, so that the cracks would appear in a region of the specimen positioned in line with that part of the piezoelectric crystal having the most sensitive characteristics.

TABLE III. - NOTCHED ULTIMATE TENSILE STRENGTHS OF MATERIALS UTILIZED IN THIS INVESTIGATION

[Notch root radius, <0.0007 in.]

Material	Tensile strength, psi
1100 Aluminum	12 000
6061-T6	48 000
2014-T6	57 700
Mild steel	50 900
Inconel	67 200

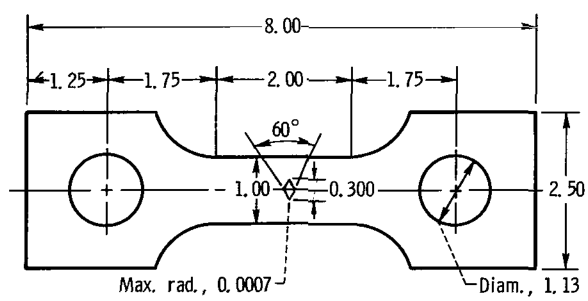


Figure 5. - Notched-sheet fatigue specimen. (Dimensions are in inches.)

Fatigue Tests

Test conditions. - Specimens of all five materials were subjected to axial tensile loads that were alternately increased and decreased in a sinusoidal pattern. The frequency was either 16 or 1970 cycles per minute depending on the expected specimen cyclic life. The ratio of minimum stress to maximum stress was maintained at 0.14 for all the materials investigated. All tests were conducted at ambient temperatures in air. At least three specimens were tested at each stress level to obtain data for the inclined portion of the S-N curves representing cyclic life to initial detectable cracks. S-N curves indicating life to fracture were also obtained for all of the materials. For 2014-T6 aluminum, an intermediate S-N curve was obtained that indicates the number of cycles to form cracks having an average length of 0.077 inch.

Fatigue tests were conducted in an axial tensile fatigue machine. The method of operation is described in reference 12. Briefly, mean tensile loads were applied by a hydraulic piston, which also compensated for specimen elongation during test. Sinusoidal alternating loads were applied by a calibrated, cam-operated lever arm. A load cell mounted in series with the specimen was used to monitor the cyclic load during test.

Application of ultrasonic detection device to fatigue tests. - The ultrasonic-reflection technique was utilized to detect cracks less than 0.005 inch in length in all the materials tested. When this technique was used, the transducer was positioned on the specimen 0.25 inch from the specimen notch. The transducer was attached to the specimen with C-type clamps (see fig. 2, p. 4) arranged so that they did not interfere with the passage of ultrasonic waves through the specimen. The reflections from the center of the notch were damped in part by the application of adhesive tape to the reflecting surface of the notch. The amplifier suppression (dc bias) was then adjusted to reduce the remaining notch signal to a low output level which was used as the zero level for crack detection. Changes in the recorded output indicated fatigue cracking at the notches. The specimens made from the softer materials were run for 10 cycles or less before the zero adjustment was made. This was done because, at the higher stresses, the notch was deformed to varying degrees in the first few cycles, which caused an instrument zero shift before cracking occurred.

The through-transmission technique required the positioning of a receiving transducer on the side of the notch opposite the transmitting transducer. In this case, amplifier gain and suppression were adjusted to provide a full-scale signal of the received energy prior to stress cycling. A decrease in the signal was indicative of the presence of a crack.

Crack-length measurement. - Upon first detection of a crack, some specimens were removed from the fatigue machine and sectioned for microscopic examination. After sectioning, the specimen surface was ground (usually until one-half the specimen thickness remained), polished, and etched to better define the crack. The image of the area containing the crack was projected on a metallograph screen at a magnification of 500, and the length of the crack image was measured to the nearest 0.010 inch (crack-length variation of 0.00002 in.). Variation of crack length within an individual specimen was determined by polishing representative samples to various depths and repeating crack-length measurements.

Specimens with longer cracks (approx 0.07 in.) were first broken in tension, and the fatigue-cracked portion of the fracture surface was then measured directly with a ruler at a magnification of 10. In some instances, surface crack length was observed at magnifications of 40 and 100 during test by means of a microscope mounted on the fatigue machine. In this way progressive crack lengths determined from the same specimen could be plotted against ultrasonic response.

As described previously, the amplitude of the received signal is dependent on the intensity of the ultrasonic waves as well as on the crack area. The intensity of the ultrasonic waves passing through a unit area of the specimen cross section is, in turn, inversely proportional to the specimen thickness. Since the crack area for a given crack length is proportional to specimen thickness, the received signal for shear waves is therefore a function of the crack length, independent of specimen thickness. Consequently, description of fatigue cracks was made in terms of length and provided a standardized comparison for all the materials investigated.

FATIGUE RESULTS

The S-N curves showing cyclic life to initial detectable fatigue cracks and cyclic life to fracture are shown in figure 6. Individual data points showing measured crack lengths are listed in table IV.

Data Obtained With Reflection Technique

The reflection technique was found to be most sensitive to the initial detection of fatigue cracks, and all of the initial crack detection data were obtained in this manner. Crack lengths as shown in the figure and listed in table IV represent the sum of the length of cracks emanating from both ends of the specimen center notch. The length of first detectable cracks in 1100 aluminum, mild steel, and Inconel, ranged approximately from 0.0005 to 0.005 inch (figs. 6(a), (d), and (e)). In 6061-T6 and 2014-T6 aluminum alloys, the length of the first detectable cracks was somewhat less, ranging approximately from 0.0005 to 0.0025 inch (figs. 6(b) and (c)). For the small initially detected cracks (all less than 0.005 in.), crack-length variation with thickness within an individual specimen was determined, for representative specimens of all materials tested, by measuring crack length at three positions along the thickness dimension. The maximum variation of crack length with thickness was found to be approximately 0.001 inch. Figure 7 shows photomicrographs of both notch roots of a representative 2014-T6 specimen after successively grinding away 27, 50, and 82 percent of the specimen thickness. The variation in crack length in this case was only 0.0003 inch.

It has long been known that fatigue cracks can exist in materials without failure occurring within a span of cyclic life that can, for all practical

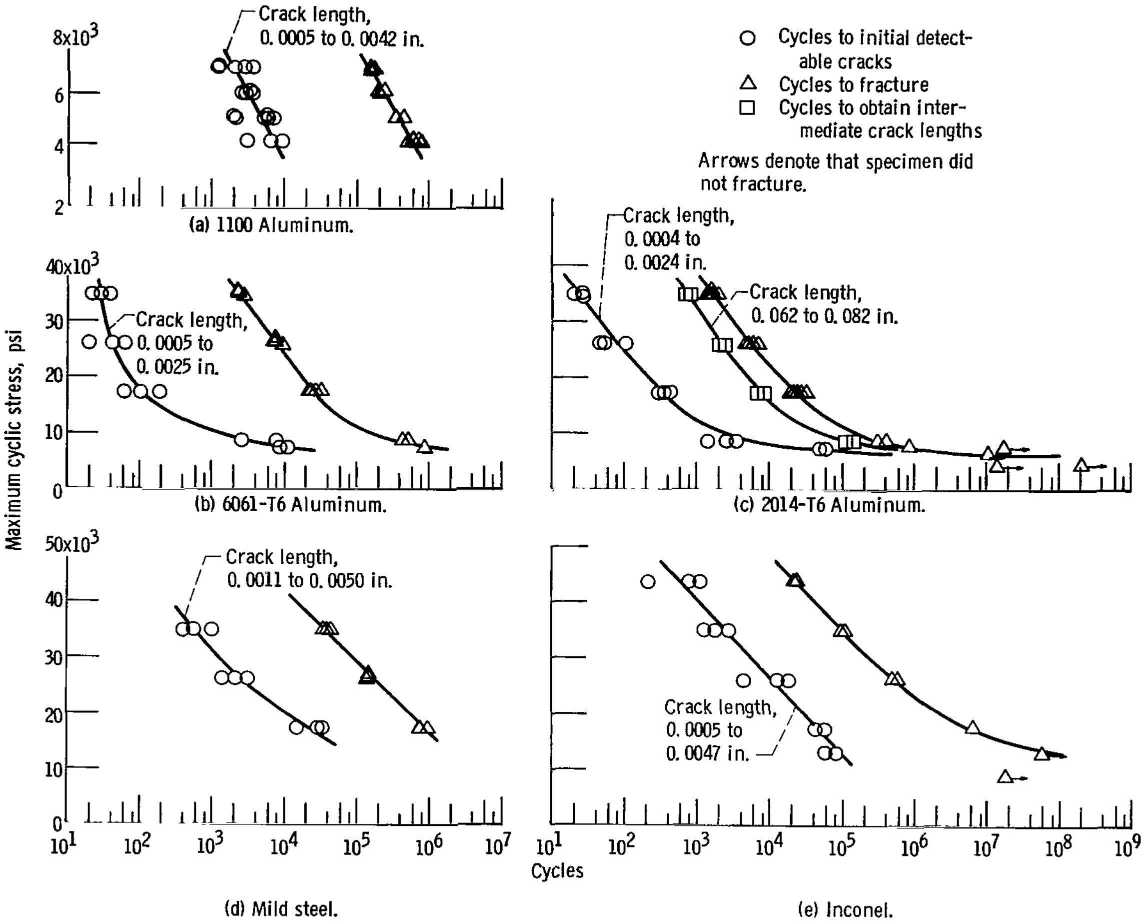


Figure 6. - Stress-life (S-N) curves showing cycles to first detectable cracks and cycles to fracture for center-notched sheet specimens. Ratio of minimum to maximum stress, 0.14.

purposes, be considered infinite. It is interesting to note that evidence of such cracks was obtained with the ultrasonic crack-detection device for 2014-T6 aluminum in this investigation (fig. 6(c)). Cracks were detected in three specimens tested at a maximum cyclic stress of 7650 pounds per square inch. Two specimens were removed from the fatigue machine at the time of crack detection; the third was run to 10^7 cycles before the test was terminated. Figure 8 shows a comparison between the cracks in one of the specimens that was removed from test after detection of the initial crack and in the specimen tested for 10^7 cycles. Crack lengths in both instances are virtually the same.

Data Obtained With Through-Transmission Technique

The through-transmission technique was utilized with the ultrasonic crack-detection device to indicate the presence of cracks having a length greater than 0.010 inch in 2014-T6 aluminum. The S-N curve representing the number of cycles until cracks of approximately 0.062 to 0.082 inch in length were formed is shown in figure 6(c). Individual data points for this curve are given in

TABLE IV. - SUMMARY OF CRACK-DETECTION DATA

(a) 1100 Aluminum.

Average crack length, 0.0023 inch.

Maximum cyclic stress, psi	Length of initial detectable crack, in.		Cycles to initial detectable crack		Percent of average life to fracture
	Single test	Average	Single test	Average	
7000	0.0005 .0008 .0014 .0028 .0032	0.0017	1200 1200 1900 2600 3500	2100	1.5
6125	0.0008 .0017 .0022 .0037	0.0021	2400 2653 3100 3200	2840	1.4
5250	0.0017 .0017 .0033 .0032 .0035 .0042	0.0029	1900 2000 4600 5100 5200 6300	4200	1.2
4375	0.0009 .0025 .0037	0.0024	2700 6000 8900	5900	1.1

(b) 6061-T6 Aluminum alloy.

Average crack length, 0.0012 inch.

Maximum cyclic stress, psi	Length of initial detectable crack, in.		Cycles to initial detectable crack		Percent of average life to fracture
	Single test	Average	Single test	Average	
35 000	0.0008 .0017 .0025	0.0017	21 28 38	29	1.3
26 250	0.0005 .0012 .0014	0.0010	20 41 59	40	0.5
17 500	0.0005 .0009 .0010	0.0008	61 99 183	144	0.6
8 750	0.0010 .0012	0.0011	2 400 7 455	4 928	1.2
7 655	0.0019 .0014	0.0017	8 500 10 700	9 600	1.1

(c) 2014-T6 Aluminum alloy.

Average length of first detectable crack, 0.0011 inch; average length of intermediate crack, 0.077 inch.

Maximum cyclic stress, psi	Length of initial detectable crack, in.		Cycles to initial detectable crack		Length of intermediate crack, in.		Cycles to intermediate crack		Percent of average life to fracture	
	Single test	Average	Single test	Average	Single test	Average	Single test	Average	First detection	Inter-mediate
35 000	0.0024 .0012 .0019	0.0018	19 25 25	23	0.076 .077	0.077	647 800	725	1.5	47.0
26 250	0.0011 .0008 .0018	0.0012	45 46 100	64	0.071 .082	0.077	2 000 2 200	2 100	1.2	38.7
17 500	0.0010 .0013 .0015	0.0013	300 342 400	347	0.063 .078 .104	0.082	6 600 7 600 10 000	8 000	1.6	32.6
8 750	0.0010 .0007 .0005	0.0007	1 400 2 500 3 400	2 800	0.062 .079	0.071	113 100 153 900	133 500	0.8	39.0
7 650	0.0004 .0004	0.0004	49 100 57 900	53 500					<1.0	

(d) Mild steel.

Average crack length, 0.0025 inch.

Maximum cyclic stress, psi	Length of initial detectable crack, in.		Cycles to initial detectable crack		Percent of average life to fracture
	Single test	Average	Single test	Average	
35 000	0.0012 .0025 .0024	0.0020	407 580 1 000	662	1.9
26 250	0.0011 .0025 .0024	0.0020	1 400 2 100 3 100	2 200	1.5
17 500	0.0021 .0050 .0035	0.0035	15 400 28 500 30 900	24 900	3.0

(e) Inconel.

Average crack length, 0.0026 inch.

Maximum cyclic stress, psi	Length of initial detectable crack, in.		Cycles to initial detectable crack		Percent of average life to fracture
	Single test	Average	Single test	Average	
43 750	0.0007 .0032 .0047	0.0029	200 748 1 148	695	3.2
35 000	0.0025 .0020 .0036	0.0027	1 250 1 700 2 700	1 883	2.0
26 250	0.0006 .0027 .0042	0.0025	4 300 13 600 17 300	11 700	2.3
17 500	0.0029 .0009	0.0019	41 100 55 800	48 450	0.8
13 125	0.0005 .0006	0.0005	56 500 79 600	68 050	No failures

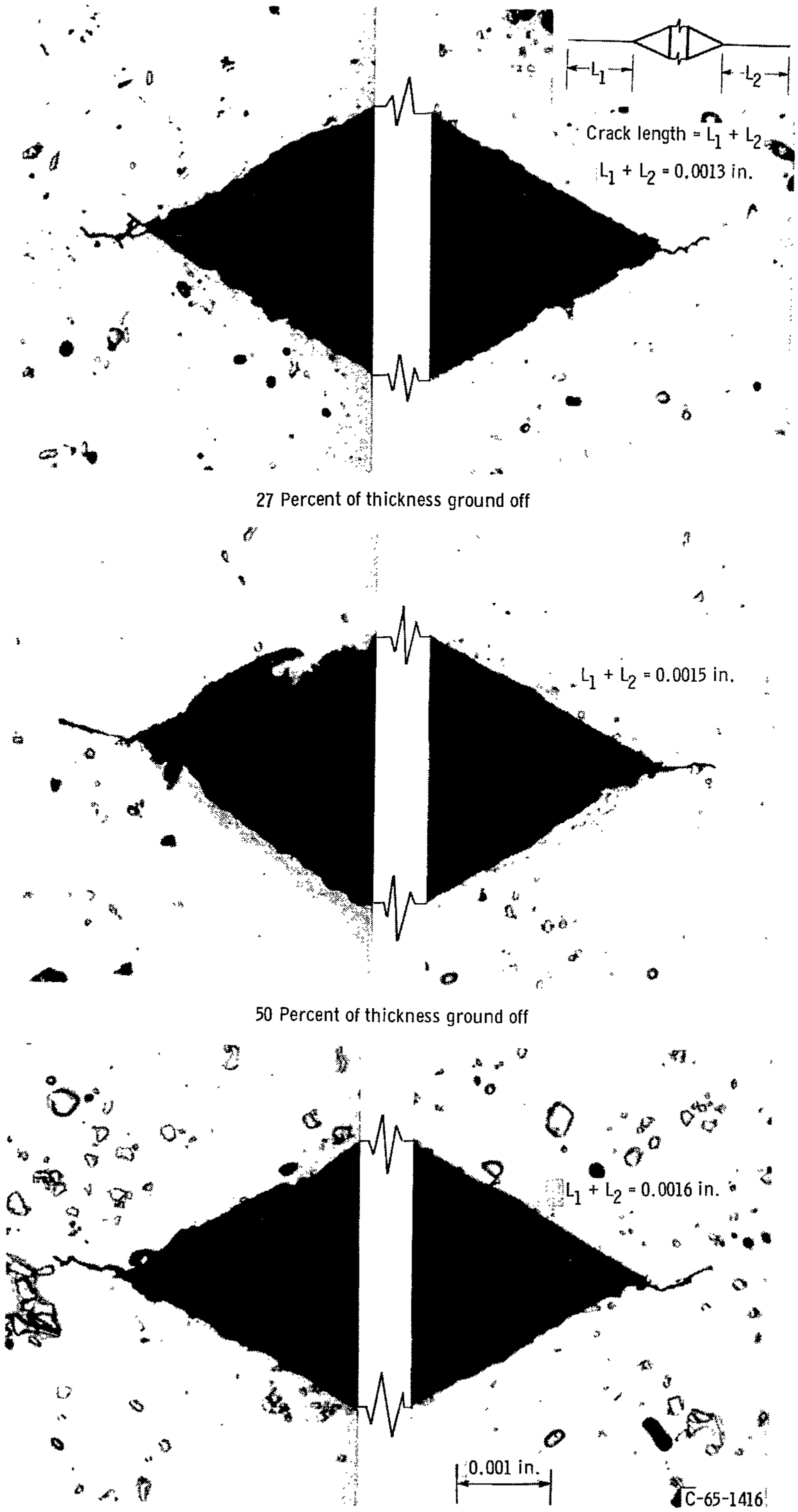
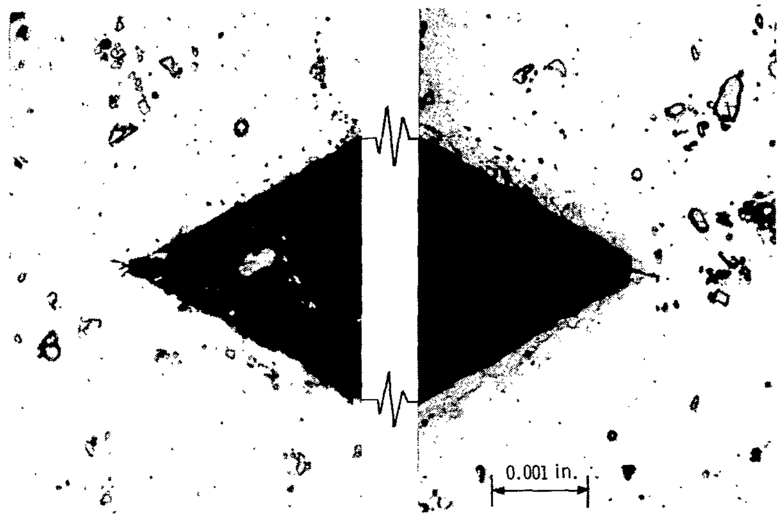
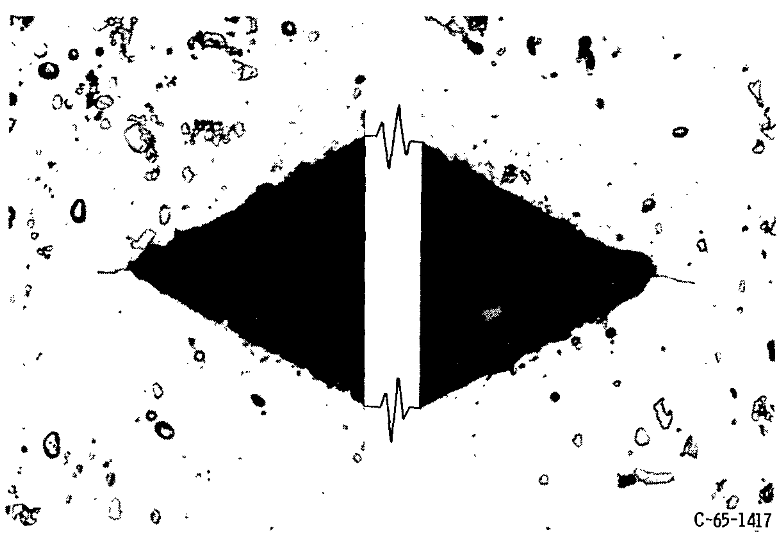


Figure 7. - Photomicrographs of 2014-T6 aluminum alloy showing variation of crack length with specimen thickness. (Only notch tips are shown.) X500.



(a) Test stopped at first indication of crack, 4.9×10^4 cycles.



(b) Test continued after first indication of crack to 1.7×10^7 cycles.

Figure 8. - 2014-T6 Aluminum alloy specimens tested at stress near endurance limit. (Only notch tips are shown.) X500.

table IV(c). These data were taken to obtain an indication of the reproducibility of the instrument output for cracks much larger than those which were detected with the reflection technique.

A full-scale signal change on the oscillograph was indicative of crack lengths ranging between 0.062 to 0.082 inch with the exception of one specimen in which the length of the crack was found to be 0.104 inch. In this instance, coupling changes may have affected the results. Except for this single case the results were fairly reproducible. The latter point is not plotted in figure 6(c). Reported crack lengths represent the average of a series of measurements made at five positions through the thickness of each specimen. Considerably greater variation in crack length with specimen thickness occurred for these longer cracks than occurred for the much shorter cracks detected by the reflection technique. Crack length in any given specimen varied as much as 0.035 inch with the longest portion usually located about midway between the surfaces. These data indicate that the through-transmission technique is apparently suitable for measuring relatively long fatigue cracks that can occur relatively late in specimen life.

DISCUSSION

Certain aspects of the operation of this crack-detection system, including operational limitations and the general applicability of the system, are discussed in the subsequent sections.

Characteristics of Fatigue Crack-Detection Device

Considerations pertinent to initial crack detection. - Detection of cracks by ultrasonic techniques is normally limited to those cracks that present a reflecting area with dimensions greater than one-half the ultrasonic wavelength. The wavelength of the ultrasonic waves generated in this system was approximately 0.026 inch; however, cracks as small as 0.0005 inch were detected because of the manner in which the crack-detection system was applied.

With the employment of notched specimens a high-amplitude signal was obtained from the notch. This signal was much larger than those arising from other sources such as grain boundaries, which could otherwise confuse interpretation of the signals. Since the crack propagates from the notch roots, the clearly distinguishable notch signal will increase further, thus making it possible to detect minute cracks by monitoring the large signal. If no reference indication (e.g., reflection from the notch) were available, the shortest detectable crack probably would have been 0.013 inch or greater.

It was determined from several preliminary tests that a recorded voltage increase in the notch signal of about 10 percent of full scale was needed to ensure that the instrument had detected a crack. Resolution of the recorded voltage was to within 2 percent of full scale. A voltage level of about 10 percent of full scale was therefore chosen to allow for possible experimental errors caused by such things as minor electronic fluctuations, slight variations

TABLE V. - CRACK-MEASUREMENT DATA FOR 6061-T6 ALUMINUM FOR VOLTAGE OUTPUTS OF 5.5 AND 11 PERCENT OF FULL SCALE

Specimen	Crack length, in.
5.5-Percent output	
1	0.0005
2	.0005
3	.0008
4	.0009
5	.0010
6	.0010
7	.0012
8	.0012
9	.0014
10	.0014
11	.0017
12	.0019
13	.0025
Average	.0012
11-Percent output	
14	0.0016
15	.0017
16	.0025
17	.0026
18	.0029
19	.0029
20	.0042
21	.0044
Average	.0029

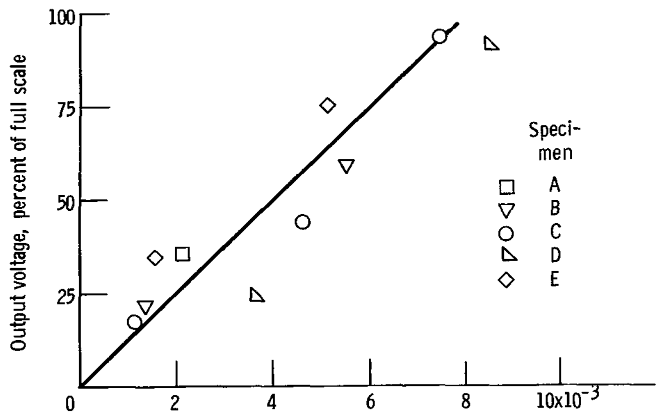


Figure 9. - Crack-detection characteristics for 2014-T6 aluminum.

in critical positioning of the transducer on the specimen, slight differences in crack orientation, and changes in coupling efficiency during the test. Of these sources of possible error, the changes in coupling efficiency probably had the greatest effect on the reproducibility of crack-detection data. Since the transducer was mounted on a stressed area of the specimen, there was some relative motion between the transducer and the specimen. This motion could have caused changes in the ability of the fluid coupling (molybdenum disulphide) to transmit ultrasonic waves. These changes could act either to improve or deteriorate the coupling efficiency. For example, if the coupling efficiency were improved before a crack formed, the instrument might give an indication of crack formation because the reflected signal from the notch would be increased; conversely, if the coupling efficiency deteriorated, indication of a crack might be delayed. In general, changes in coupling efficiency were small and were not detectable with the coupling monitor crystal.

Relation between output voltage and crack length with reflection technique. - The relation between output voltage and crack length was investigated for two of the materials: 6061-T6 and 2014-T6 aluminum. Table V shows crack-detection data for specimens of 6061-T6 aluminum alloy examined after instrument outputs of 5.5 and 11 percent of full scale had been obtained. The average crack length for the lower output voltage was 0.0012 inch, while for the higher output it was 0.0029 inch. Thus, it is evident that the output voltage was directly related to crack length. The spread in crack length relative to the average crack length, however, is greater for the lower voltage output than for the higher voltage output.

The relation between instrument output and crack length was further explored with 2014-T6 aluminum. Figure 9 shows a plot of crack length against output voltage for this material. The crack lengths were measured on the specimen surface with a microscope at a magnification of 100 while the test specimen was under load in the fatigue machine. The data points were taken from five specimens fatigued at different stress levels. The output was linear with respect to crack length over the full scale of the oscillograph. The deviation from the curve, referenced to full scale (0.008 in.), is about ±25 percent.

For crack lengths greater than 0.010 inch the relation between output voltage and crack length was no longer linear, and scatter increased markedly; therefore, calibration of the instrument for longer crack lengths with the reflection technique was not possible. The data of figure 9, however, indicate that the instrument has at least a limited capability for specifying crack length as well as detecting the presence of small fatigue cracks.

Effect of cyclic stress on sensitivity to presence of small cracks. - Responses from the load cell mounted in series with the specimen were recorded simultaneously with ultrasonic output voltage. The presence of a crack could be noted earlier in cyclic life if measurements were taken while the specimen was subjected to the maximum cyclic stress than while it was subjected to the minimum cyclic stress because the adjacent metal surfaces created by a small crack are pulled apart to a greater degree at maximum load than at any other tensile load. Consequently, ultrasonic waves would tend to be reflected at high loads; whereas, they would tend to be transmitted across the crack interface at low loads. In view of this, it appears that output voltage readings should always coincide with the applied cyclic stress at which the crack surfaces are most widely separated in order for this instrument to be operated in the most efficient manner possible for the detection of small cracks.

General Observations

The fatigue data show that, in the sharply notched specimens utilized, cracks were detected within 1 to 3 percent of the total life to fracture for all materials tested over the range of stresses considered. Although the materials varied widely in mechanical properties, it was nevertheless possible to detect cracks with this device at a very small fraction of the total life to fracture. It should be noted that, although approximately the same fraction of total life to fracture was used in forming the first detectable cracks in all the materials investigated, the actual number of cycles required to form such cracks varied considerably from material to material. This is evident from table IV (p. 14).

In order to determine whether the ultrasonic testing apparatus had a deleterious effect on fatigue behavior, specimens of mild steel and 2014-T6 aluminum were fatigue tested to failure without the transducer attached. Fatigue life was essentially identical with that obtained for similarly stressed specimens subjected to simultaneous ultrasonic pulses and fatigue testing. Thus, the effects of the additional mass associated with the transducer and clamp, the presence of molybdenum disulphide on a portion of the specimen surface, and the acoustical energy associated with ultrasonic testing did not adversely affect fatigue life.

Although the ultrasonic system for detecting fatigue cracks developed in this investigation is intended primarily for use as a research tool, the results indicate that it may also have applications for fatigue crack detection in the field. For example, the notched specimen employed in this study may be considered analogous to critically stressed airplane components containing stress risers. By detecting small flaws in such components while a prototype airplane is being subjected to anticipated fatigue loads on the ground, substantial savings in time might be achieved over cumbersome visual inspection techniques. Similarly, application of the device to known critically stressed sections of an aircraft after specified periods of flight time might indicate the presence of minute cracks early enough to allow time for remedial measures to be taken. Further research is of course needed to make this ultrasonic crack-detection system suitable for such practical applications.

SUMMARY OF RESULTS

An ultrasonic system was developed and used to detect and measure minute fatigue cracks in center-notched sheet specimens of unalloyed aluminum, two aluminum alloys, a mild steel, and a nickel-base alloy. Both reflection and through-transmission techniques were employed. Actual lengths of detected cracks were determined by metallographic examination. Stress-life (S-N) curves of life to initial detectable crack as well as life to fracture were obtained.

1. With the reflection technique, fatigue cracks that ranged approximately from 0.0005 to 0.005 inch in length were detected during fatigue testing of the more ductile materials (i.e., pure aluminum, mild steel, and Inconel) and cracks ranging approximately from 0.0005 to 0.0025 inch in length were detected in the less ductile materials (6061-T6 and 2014-T6 aluminum alloys).

2. In the sharply notched specimens utilized in this investigation, cracks were detected within approximately 1 to 3 percent of total specimen life, for all of the materials considered, over the range of stresses considered.

3. The reflection technique was more sensitive to the detection of minute fatigue cracks than the through-transmission technique. Thus, it was possible to detect much smaller cracks with the reflection technique.

4. The through-transmission technique gave consistently reproducible output voltages for cracks on the order of 0.062 to 0.082 inch in 2014-T6 aluminum. This reproducibility was better than that obtained with the reflection technique for similarly long cracks. The through-transmission technique thus appears to be better suited for measuring the length of cracks greater than about 0.010 inch.

5. The effects of crack orientation on output voltage with the reflection technique was studied by means of slots machined into flat plates. Slot surfaces normal to the direction of the ultrasonic waves produced the greatest output voltage. The further the slot surface deviated from a position normal to

the wave propagation direction, the smaller the output became, even though the slot surface area when projected on a plane normal to the wave was constant.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 10, 1965.

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